

Measurement of brightness temperature of two-dimensional electron gas in channel of a high electron mobility transistor at ultralow dissipation power

A.M. Korolev,^{1, a)} V.M. Shulga,¹ O.G. Turutanov,² and V.I. Shnyrkov²

¹⁾*Institute of Radio Astronomy, NAS of Ukraine, Chervonopraporna St. 4, Kharkov 61002, Ukraine*

²⁾*B. Verkin Institute for Low Temperature Physics and Engineering, NAS of Ukraine, Lenin Ave. 47, Kharkov 61103, Ukraine*

(Dated: 26 February 2015)

A technically simple and physically clear method is suggested for the direct measurement of brightness temperature of two-dimensional electron gas (2DEG) in the channel of a high electron mobility transistor (HEMT). The usage of the method was demonstrated with the pseudomorphic HEMT as a specimen. The optimal HEMT dc regime, from the point of view of the "back action" problem, was found to belong to the unsaturated area of the static characteristics possibly corresponding to the ballistic electron transport mode. The proposed method is believed to be a convenient tool to explore the ballistic transport, electron diffusion, 2DEG properties and other electrophysical processes in the heterostructures.

Keywords: brightness temperature, HEMT, ultra-low power consumption, 2DEG, back action

^{a)}Electronic mail: korol.rian@gmail.com

I. INTRODUCTION

It is a common knowledge that the impact of a measuring device onto the object-under-test should be minimized if working with signal sources of essentially quantum nature. This is a general problem of non-disturbing quantum measurements. For electronic detecting facilities, especially amplifiers, this means minimizing the energy, of noise or other origin, irradiated backwards to the object-under-test. The effect is a so called "back action", the phenomenon causing uncontrolled destruction of a quantum state of the object, e.g., the qubit decoherencing, etc.¹⁻³. The back action is detected and requires a quantitative description in a wide frequency band, orders of magnitude wider than the amplifier operation frequency band. Therefore, the "equivalent noise temperature" (T_n) determined for a relatively narrow operation frequency band of the amplifier (receiver) is an inadequate term here. Instead, one should say about wide-spectrum brightness temperature of the amplifier and its active elements, at both the input and output "terminals".

The amplifiers intended for ultra-low temperature applications (to amplify the signals from quantum detectors, single electron transistors and variety of other quantum structures) are typically based on the field-effect transistors. Among them, a class of HEMT is distinguished, the field-effect transistors with high electron mobility. HEMTs feature a very wide operational frequency band while field-induced as opposed to thermally-generated current-carrier electrons (two-dimensional electron gas, 2DEG) in the channel principally enable the transistor functionality down to the absolute zero temperature. Owing these advantages of the HEMTs they are widely used in ultra-sensitive readout amplifiers^{4,5} for quantum devices signals. Consequently, the quantitative description of the back action as applied to HEMTs is a hot issue.

Thermal noise is generated in the HEMT input (gate-source) terminals due to power dissipation in the input circuit of the transistor. The dissipative losses come mainly from the gate metallization resistance, the under-gate channel resistance and the source resistance. The corresponding irradiation (for perfect matching, or zero input reflection coefficient) is characterized by the gate temperature T_g which is close to the physical temperature of the transistor crystal lattice T_{lat} . Cooling down to the cryogenic temperatures is an effective method to suppress the thermal irradiation. If an ultra-deep cooling is supposed, it should be accompanied by a considerable decrease (down to a few microwatts and less) in the transistor

consumed/dissipated power to avoid excessive Joule overheating of its active area. The situation with overheating becomes more severe because of low thermal conductivity of the heterostructures⁶. The low cooling capacity of the ultra-low-temperature cryorefrigerators, especially below 100 mK, also strongly limits the HEMT dissipated power. Provided if the heat sink is effective, the input-circuit-generated thermal noise is reduced sufficiently and can be neglected regarding the back action.

The "hot" electrons irradiation from the gate-drain channel region, being another cause of the back action, also contributes substantially to T_n . A high effective electron temperature T_d (drain temperature) exceeding the lattice temperature by two orders of magnitude is inherent for this mechanism. The irradiation of the 2DEG in gate-drain part of the channel goes backward to the input via intrinsic drain-gate capacitance of the transistor. The excitation of the waveguide modes by the output circuit in the conductive cavity (where the amplifier is placed and often the signal source) is an additional way.

The effect of T_d can be roughly estimated using the reverse transmission gain (S_{12}) from the transistor S-matrix. Typically, S_{12} is about -20...-30 dB at 1 GHz frequency. The S_{12} rises almost linearly with frequency so the effect of T_d can prevail over T_g . If the amplifier has a high input impedance (S_{12} is defined for 50- Ω network), then the reverse transmission increases stimulating the search for the ways of T_d reduction.

The T_d and T_g are used to calculate basic noise characteristics of a transistor, namely, the minimal noise temperature, the optimal source impedance and the noise conductivity⁷. The both T_d and T_g figures are extracted from a series of the noise measurements by solving the inverse problem⁸ on the basis of the electrophysical transistor model which is inevitably limited to certain frequency band and temperature range. Integrally, the extraction procedure is sophisticated and ambiguous.

In the context of the back-action problem, the characteristics of the existing energy flows disturbing the quantum object should be found. The temperature is a natural quantifier of the chaotic (noise) irradiation. So, the task is rather to measure directly the brightness temperature than to solve the inverse problem on extraction of T_d , T_g or other similar noise invariants⁹.

First, to measure T_d instrumentally, the contribution of the amplified noise of the input circuit to the integral output noise irradiation of the transistor should be excluded. Referring to the modern transistors with cut-off frequencies of tens and more gigahertz, such an

elimination is hard enough because of stability problem. Moreover, it becomes much more complicated under the deep-cooling conditions. However, the ultra-low power consumption of the transistor associated with deep-cooled amplifiers results in decrease in the cut-off frequency by two orders of magnitude while the stability factor exceeds the unity. Consequently, the stability is not further an issue, and the direct instrumental measurement of T_d become possible.

In this work we propose a simple method to measure directly the brightness temperature of the 2DEG in a HEMT channel. The results of the measurements are discussed and the recommendations on the choice of the HEMT dc regime are formulated concerning the back action phenomenon.

II. THE BRIGHTNESS TEMPERATURE MEASUREMENT TECHNIQUE

The simplified diagram of the experimental setup is shown in Fig.1. The essence of the technique are by-turn measurement and subsequent comparison of the powers of the two signals. The first one is produced by the output circuit of the transistor-under-test (Q1), the second one is the reference, taken from a variable resistor R whose temperature is equal to the ambient temperature. During the calibration procedure, the resistance R is set equal to the differential resistance of the channel in a specified point of the transistor static characteristics. The measurement cycle is described below in more detail.

The transistor gate is ac-shortcd to the source by C1 to exclude the amplified input circuit noise from the net output signal.

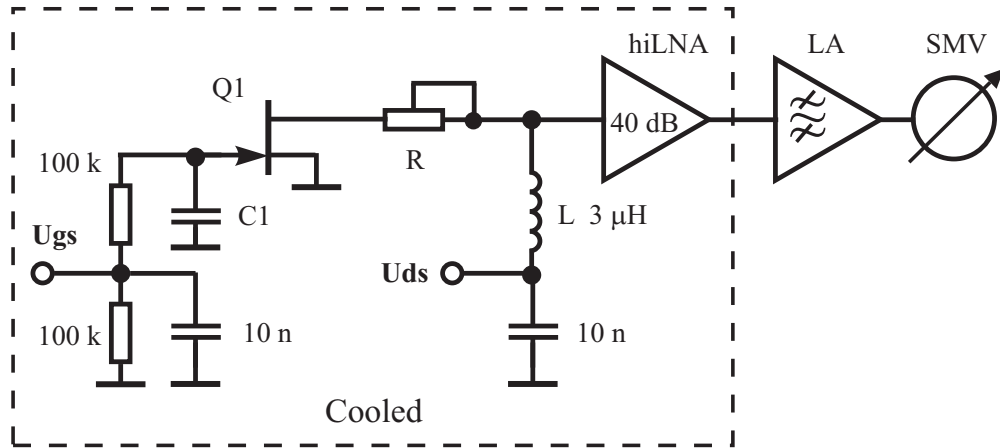


FIG. 1. The simplified diagram of the testing setup.

The self inductance of the capacitor C1 (SMD 0603, 330 pF) along with the inductance of the Q1 gate terminal does not exceed 3 nH. The associated reactance at a mean frequency (50 MHz) of the operational range is inductive and not greater than $4\ \Omega$ and the capacitive reactance of the gate-source of more than $3\ \text{k}\Omega$. Under these conditions, only the noise component representing the source resistance noise is amplified by the transistor adding to T_d . This resistance does not exceed $3\ \Omega$ for practically all low-power HEMTs. Taking into account that the transistor voltage gain does not exceed 5 under the microcurrent dc regime, it is easy to show that the contribution of the source noise in the output signal is less than 1%.

The transistor Q1 and the variable resistor R are placed close to the instrumental amplifier to minimize the shunt capacitance. A three-stage HEMT (AVAGO ATF35143) high input impedance ($100\ \text{k}\Omega$), low-noise cooled amplifier (hiLNA in Fig. 1) is used as the instrumental amplifier. The hiLNA gain is about 40 dB, the operational frequency band is 20 to 100 MHz. The integral noise temperatures of the hiLNA are $2.3\pm0.5\ \text{K}$ and $1.2\pm0.5\ \text{K}$ at the source resistance of $10\ \Omega$ and $1000\ \Omega$, respectively, and the ambient temperature $T_{amb} = 4.2\ \text{K}$. The amplifier circuitry is similar to the earlier reported devices¹⁰.

The measuring circuit is a low-Q parallel tank consisted of the resistor R and HEMT channel resistance, the capacitance of the wires, pads and hiLNA input (totally 5 pF) and the inductance L ($3\ \mu\text{H}$).

A linear amplifier (LA) with a band-pass filter (40...80 MHz) is placed next to the hiLNA. The specified frequency band (namely, the lower edge) is chosen in order to exclude the $1/f$ noise of Q1.

The output signal level is measured by a square-meter voltmeter (SMV) within an accuracy of better than 1%. The multisection filters are put into the supply circuits (not shown in Fig. 1) and the test unit is electromagnetically shielded. The measurement errors are 0.1% and 1.5% for the dc voltages and currents, correspondingly.

The measuring cycle is a three-stage one. First, the resistor R is set to zero resistance, and the static characteristics of the transistor are measured. The drain-source resistance r_d is calculated from the data obtained as a function of U_{ds} and U_{gs} . The SMV readouts are taken for each calculated r_d . According to the measurement procedure and Nyquist theorem, the SMV voltage, which is proportional to the output signal power, can be written as:

$$\langle U_m^2 \rangle = \langle U_0^2 \rangle + 4kr_d T_{el} G_m \Delta F_m, \quad (1)$$

where $\langle U_m^2 \rangle$ is the mean square of the measured output voltage at a specified drain-source resistance r_d , $\langle U_0^2 \rangle$ is the mean square of the measured output voltage at $r_c = 0$ (see below), k is the Boltzmann constant, T_{el} is the brightness temperature of the noise irradiation of the transistor channel, G_m and ΔF_m are the total gain and effective pass band of the measuring system, correspondingly, at the specified r_d .

The second stage is a calibration. The transistor is zero-biased and maximally opened ($U_{ds} = U_{gs} = 0$). The channel resistance r_d is minimal ($r_{dmin} = 8 \pm 1 \Omega$ for ATF36077) and fully linear. The noise generated by r_d is purely thermal (white). It adds to the noise of the calibration resistor R with resistance r_c . The calibration includes tuning the calibration resistor R in the range of 0...670 Ω while the SMV readout is synchronously taken. In a manner similar to (1), we write the equation for the SMV output signal:

$$\langle U_c^2 \rangle = \langle U_0^2 \rangle + 4kr_c T_{amb} G_c \Delta F_c, \quad (2)$$

where $\langle U_c^2 \rangle$ is the mean square of the measured output voltage at a specified resistance r_c of the calibration resistor R (exactly, $r_{dmin} + r_c$), T_{amb} is the physical temperature of the calibration resistor R, G_c and ΔF_c are the total gain and the effective pass band of the measuring system, correspondingly, at the specified r_c .

Finally, an expression for T_{el} can be derived from (1) and (2) taking $G_c = G_m$, $\Delta F_c = \Delta F_m$. These equalities are valid if the experimental values are taken from the data array with the selection rule $r_d = r_c$. Then we obtain:

$$T_{el} = T_{amb} \frac{\langle U_m^2 \rangle - \langle U_0^2 \rangle}{\langle U_c^2 \rangle - \langle U_0^2 \rangle} \quad (3)$$

To simplify the measurement and calculation procedures, a few assumptions were made when writing (1)-(3).

(i) $\langle U_0^2 \rangle = \text{const}$ is assumed, i.e. the noise temperature of the instrumental amplifier (hiLNA) does not depend on the source resistance. Actually, it varies (see above) although always staying below the temperature to measure, T_{el} .

(ii) $\langle U_0^2 \rangle$ is supposed to be measured at $r_c = 0$.

In fact, the minimal value $r_{cmin} = r_{dmin} \approx 8 \Omega$ (for ATF36077).

(iii) It is believed that the dc channel resistance r_d is equal to the ac one, at the measurement frequency (40-60 MHz). In reality, the ac channel resistance is less by a few percent.

All the assumptions made are not too rough, and the systematic absolute error (see section III) does not exceed 2 K. Nevertheless, it should be taken into account when T_{el} is about several kelvins. When the measured T_{el} is of some tens kelvins (the most important and interesting range), the error is determined by the accuracy of the instrumental measurement being, by our estimate, of about 10% of the measured value. To the authors' opinion, this error is acceptable in the context of this work.

Additionally, the following should be clarified here. The drain temperature T_d , as a parameter in the two-temperature Pospeshalski noise model⁷, actually represents the effective temperature of the 2DEG in the saturated region (roughly, the gate-drain region) of the HEMT channel. Meanwhile, the expression (3) that we obtained for T_{el} represents an averaged 2DEG temperature throughout the whole channel including the source-gate part with its temperature which is always close to T_{lat} . It is the 2DEG temperature that we designate by T_{el} . It is measured directly and has a clear physical sense. However, T_d and T_{el} do not differ too much since the resistance of the source-gate region is about 1/100 of the total channel resistance.

The measurement of T_{el} can, in principle, be done without the calibration resistor, using the transistor noise instead at $U_{ds}=0$, $I_d=0$. However, in practice this requires an extra (negative) bias voltage which could cause, for some transistors, the gate leakage noise to emerge.

III. BRIGHTNESS TEMPERATURE MEASUREMENT RESULTS AND DISCUSSION

The pseudomorphic HEMT AVAGO ATF36077 was chosen as a test object. We believe this transistor is a good representative of low-power HEMTs. Additionally, as our practice show, ATF36077 has a very low gate leakage current and a high mechanical stability during multiple thermal cycling. The ATF36077 static characteristics show no hysteresis. All said above makes ATF36077 a suitable object for testing the proposed measurement method.

The bias voltage and, correspondingly, the maximal drain current were chosen so that the transistor dissipated power P_c would not exceed 200 μ W. The larger P_c values are beyond

the subject of this work. Also, at $P_c > 50 \mu\text{W}$ the transistor-under-test should be carefully monitored for a parasitic oscillation to emerge which is provoked by the gate grounding. The consumption current of the hiLNA is a suitable indicator of the parasitic oscillations.

The measurements were taken at 4.2 K, 78 K and 290 K when developing the technique. The results of the measurements at 4.2 K are reported below.

Fig. 2 demonstrates the static characteristics and the electron temperature for ATF36077. Let us start with these data to estimate the measurement error. To do this, we note that the measured T_{el} is assumed to be equal to T_{amb} when $U_{ds} = 0$, $I_d = 0$. It is quite reasonable from the physical point of view. Then the difference between T_{el} and T_{amb} in the origin of the static characteristic branch ($U_{ds}=0$) can serve as a measure of the absolute error. The data show that the systematic error does not exceed 2 K.

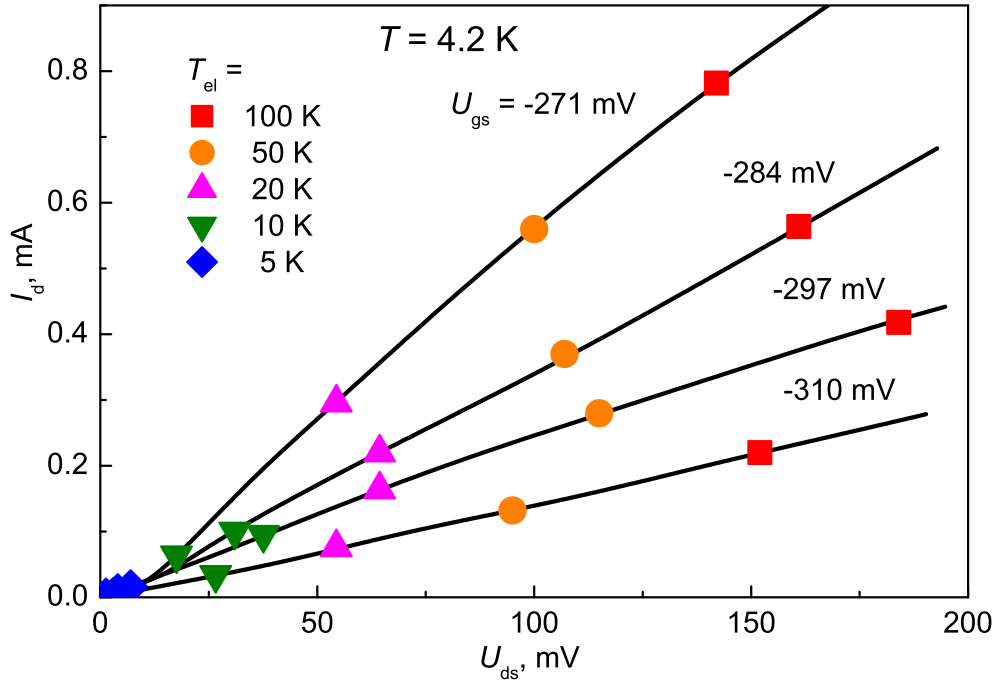


FIG. 2. (Color online) The static I-V characteristics of ATF36077 and the electron temperature at 4.2 K.

Let us take conventionally $S_{12} = -10$ dB as a measure of the back action. Also, we define the criterion of the acceptable irradiation in the direction of the signal source: the temperature of such an irradiation must not be higher than $2T_{lat}$, that is $T_{el} \leq 20T_{amb}$. Bearing in mind these definitions, a recommendation useful in designing the amplifiers with reduced back action can be derived from Fig. 2. Namely, the maximal acceptable value of

U_{ds} is 150 mV for HEMT operating at $T_{amb} = 4.2$ K.

Fig.3 shows the electron temperature T_{el} as a function of the drain current I_d at fixed drain-source voltages U_{ds} .

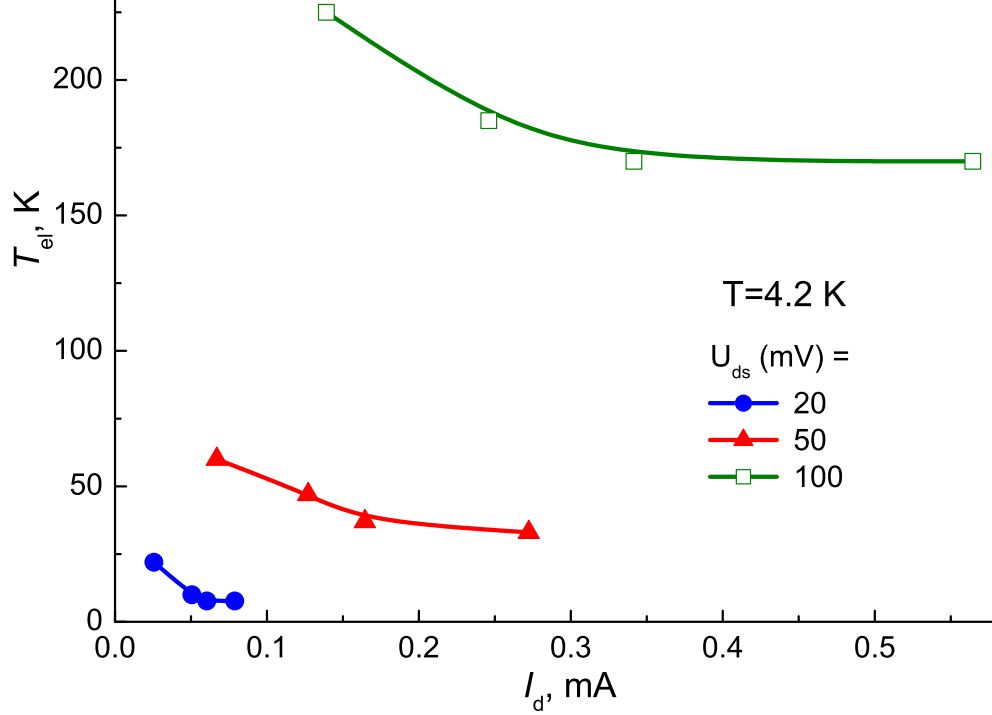


FIG. 3. (Color online) The electron temperature as a function of the drain current at fixed drain-source voltages.

It is clearly seen that $T_{el}(I_d)$ plot tends to a saturation and, there is no increase of the electron temperature with the current anyway. This witnesses for a negligible contribution of the channel diffusion noise induced onto the gate. Therefore, the gate is "well-grounded" while the operation frequency and the circuit design are adequate.

The T_{el} as a function of U_{ds} at fixed drain currents is plotted in Fig. 4. It should be noted at once that the doubled electron temperature ($T_{el} = 2T_{amb}$) is observed at the voltages much higher than expected threshold values (of order of 1 mV) approximately following from the condition $kT = eU_{ds}$. The effect could evidence for the ballistic (collision-free) electron transport at corresponding parts of the static characteristics.

A distinctive bend of the curve taken at the drain current of 100 μ A may be associated with the threshold of the optical phonon scattering mechanism activation (approximately 30 eV for the A3B5 semiconductors). The corresponding dc regime ($I_d \approx 0.1$ mA, $U_{ds} \leq 35$ mV)

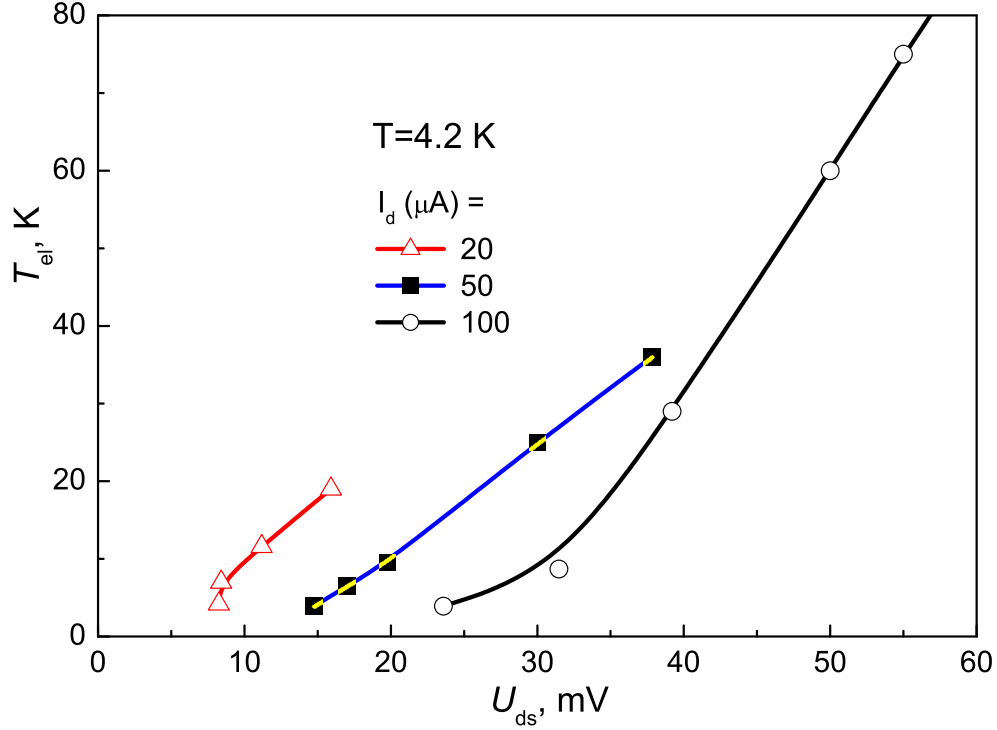


FIG. 4. (Color online) The electron temperature as a function of the drain-source voltage at fixed drain currents.

can be recommended for the first-stage transistors in the amplifiers with minimized back action intended to function at subkelvin temperatures. The HEMT ability of working at ultra-low supply voltages in the unsaturated region of the static characteristics was reported earlier in^{11,12}. The absence of the "bend" in the plots corresponding to the drain currents 20 and 50 μA is most likely due to the expansion of the under-gate depletion region towards the source. This effect probably causes the paradoxical rise of T_{el} with decreasing the channel current (Fig. 4) as well.

The above estimates and the plots analysis is rather qualitative. They aimed, in the context of this work, to the demonstration of reasonability of the measurement of the electron temperature in studying electrophysical processes in HEMTs and finding the optimal regimes from the point of view of the back action problem.

To estimate the back action at low frequencies where $1/f$ noise predominates, it is necessary to measure the amplifier noise temperature with the standard procedure⁴.

IV. SUMMARY

A technique is suggested in this paper for the direct measurement of the brightness temperature of the 2DEG in a HEMT. The technical simplicity and clear physical sense of the measurement results makes the proposed method a convenient tool for further studies of the delicate electrophysical processes such as the ballistic electron transport and diffusion, the 2DEG properties and so on.

Grounding on the results of the 2DEG brightness temperature measurements, the recommendations are put for choosing the HEMT dc regimes which are the best concerning the back action. It is found that the optimal HEMT operation points to minimize the back action lie in the unsaturated area of the static characteristics that possibly corresponds to the electron ballistic transit.

REFERENCES

- ¹K. Bladh, T. Duty, D. Gunnarsson, and P. Delsing, *New J. of Phys.* 7, 180 (2005).
- ²M. Grajcar, A. Izmalkov, E. Il'ichev, Th. Wagner, N. Oukhanski, U. Huebner, T. May, I. Zhilyaev, H.E. Hoenig, Ya.S. Greenberg, V.I. Shnyrkov, D. Born, W. Krech, H.-G. Meyer, A. Maasen van den Brink, and M.H.S. Amin, *Phys. Rev. B*, 69, 060501 (2004).
- ³W.W. Xue, Z. Ji, Feng Pan, Joel Stettenheim, M.P. Blencowe, & A.I. Rimberg, *Nature Physics* 5, 660 (2009).
- ⁴N. Oukhanski and E. Hoenig, *Appl. Phys. Lett.* 85, 2956 (2004).
- ⁵M.P. DeFeo and B.L.T. Plourde, *Appl. Phys. Lett.* 101, 052603 (2012).
- ⁶J.J. Bautista and E.M. Long, *The Interplanetary Network Progress Report.- IPN PR* 42-170, 1 (2007).
- ⁷M.W. Pospieszalski, *IEEE Trans. Microwave Theory & Tech.* 37, 1340 (1989).
- ⁸J. Stenarson, M. Garcia, I. Angelov, and H. Zirath, *IEEE Trans. Microwave Theory & Tech.* 47, 2358 (1999).
- ⁹G. Dambrine, J.-M. Belquin, F. Danneville, and A. Cappy, *IEEE Trans. Microwave Theory & Tech.* 46, 1231 (1998).
- ¹⁰N. Oukhanski, M. Grajcar, E. Il'ichev, and H.-G. Meyer, *Rev. Sci. Instrum.* 74, 1145 (2003).

¹¹A.M. Korolev, V.I. Shnyrkov and V.M. Shulga, Rev. Sci. Instrum. 82, 016101 (2011).

¹²A.M. Korolev, V.M. Shulga, S.I. Tarapov, Cryogenics 60, 76 (2014).